Signal Conversion

Signal conversion is the process of converting one type of signal into another to facilitate the transmission and processing of information between different systems or devices.

ADC (Analog to Digital Converter)

- **Converts continuous analog signals into discrete digital signals**. This is often used to convert analog data from sensors into digital form for processing by computers or digital systems.
- For example, converting the voltage signal from a temperature sensor into digital data for processing in a microcontroller.

Key Parameters:

- Resolution

- Sample Rate

- SNR (Signal-to-Noise Ratio)

Resolution

Resolution determines the smallest voltage change an ADC can distinguish. **Higher resolution results in a finer digital signal output, allowing for more precise representation of the analog signal's variations.** Typically, the accuracy of an ADC instrument increases with higher resolution.

Sample Rate

Sampling is the core process of DSP (Digital Signal Processing) and digital signals. Sampling extracts segments from continuous-time signals, converting them into discrete-time signals. **The core of sampling is determining the appropriate sampling frequency to accurately reconstruct the original signal.** This frequency must adhere to the Nyquist Rate.

Nyquist Theorem

- The Nyquist theorem states that to **accurately reconstruct the original analog signal, the sampling rate must be at least twice the highest frequency of the signal.**
- **Insufficient sampling rate leads to aliasing,** where high-frequency signals are misrepresented as low-frequency signals.

Nyquist Frequency

- **The Nyquist frequency is half the sampling rate.** It represents the highest frequency component that can be accurately reconstructed.
- f_N = f_s / 2, where f_N is the Nyquist frequency, and f_s is the sampling rate.
- **If the input signal frequency exceeds the Nyquist frequency, aliasing occurs,** causing high-frequency components to be misidentified as low-frequency components.
- Example: If the sampling rate f_s is 10 kHz, the Nyquist frequency f_N is 5 kHz. Any signal frequency above 5 kHz will lead to aliasing.

Nyquist Rate

- **The Nyquist rate is twice the highest frequency in the signal.** According to the Nyquist theorem, **the sampling frequency must be at least the Nyquist rate to reconstruct the signal without distortion.**
- f_r = 2 *f_max, where f_r is the Nyquist rate, and f_max is the highest frequency of the signal.
- The sampling rate must be at least the Nyquist rate to avoid aliasing and accurately reconstruct the signal.
- Example: If the highest frequency f_max is 5 kHz, the Nyquist rate f_r is 10 kHz. Therefore, the sampling rate must be at least 10 kHz.

Aliasing

Aliasing occurs when the sampling rate is insufficient to capture all details of the analog signal, causing high-frequency components to be misrepresented as low-frequency components. This results in distortion and inconsistency between the reconstructed signal and the original signal.

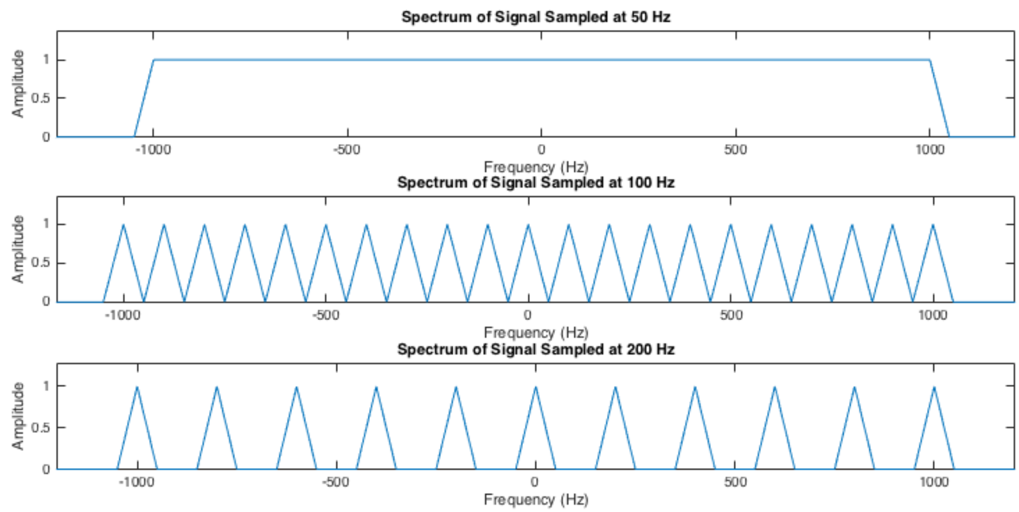
Causes of Aliasing:

- When the sampling rate is below the Nyquist rate, components higher than the Nyquist frequency cannot be correctly captured, appearing as lower frequency signals, causing distortion.

Methods to Prevent Aliasing:

- Anti-Aliasing Filter: Before sampling, it is usually necessary to apply a low-pass filter to the continuous signal. **(Low-pass filtering removes values above the cutoff frequency and only allows frequencies below it to pass through.)** This process filters out the high-frequency components and removes those above the Nyquist frequency, thus preventing aliasing.

- Increase Sampling Rate: Ensure the sampling rate is at least twice the highest frequency component in the signal to meet the Nyquist theorem's requirements.



If the sampling frequency is insufficient, the signal's spectrum images will overlap.

$F_s > 2.BW$

Working Principle of ADC

Analog random signal → Sampling → Quantization → Encoding → Digital signal

Quantization

Quantization converts sampled continuous amplitude values into discrete amplitude values, **typically introducing errors as the continuous signal is approximated to discrete values.**

$$V_{in} = \sum_{n=0}^{N-1} b_n 2^n \frac{V_{ref}}{2^N}$$

Mathematical Description of Quantization:

- Vin Input voltage — b_n: Series bits, taking values of 0 or 1
- V_ref: Reference voltage — N: Number of quantization bits

The formula indicates that the input voltage Vin is decomposed into a combination of bit positions b_n, each multiplied by the corresponding weight (2^n * Vref / 2^N)

Quantization Levels:

Quantization levels refer to the number of discrete voltage values an ADC can distinguish. The formula 2^N indicates the number of quantization levels, where N is the number of bits. **More bits mean more quantization levels, resulting in higher signal accuracy.**

Quantization Error:

The difference between the input signal and the quantized signal. Quantization introduces errors as continuous signals are approximated to discrete values. The size of the quantization error is related to the number of quantization levels—the more levels, the smaller the error.

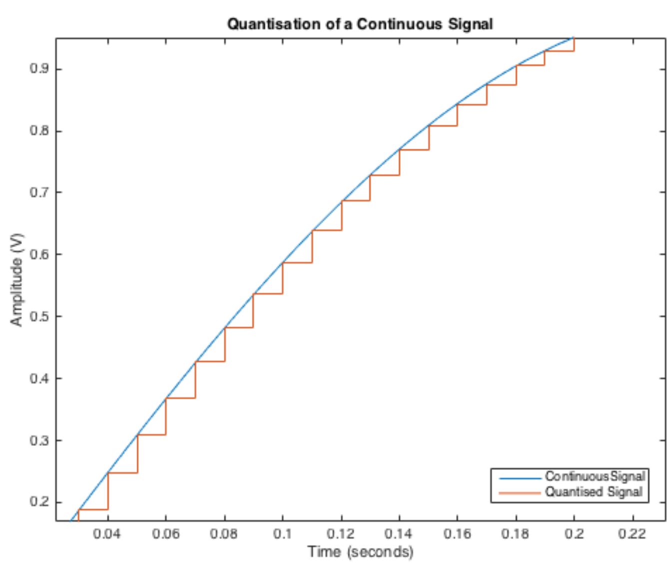
Quantization Error Formula:

For an input signal x(t) and quantized signal x_q(t), the quantization error e(t) can be expressed as: **e(t) = x(t) - x_q(t)**

Average Quantization Error

Assuming the quantization error is uniformly distributed (i.e., all values within a quantization interval occur with equal probability), the average quantization error (mean square error) can be calculated.

$$\epsilon = \frac{\pm q}{2} = \pm A.2^{-N}$$



- Continuous Signal: A smooth curve representing the true analog signal.

- Quantized Signal: A stepped line representing the quantized digital signal. The quantized signal approximates the continuous signal, with changes at each quantization level.

Encoding

Encoding converts the quantized discrete signal into a digital signal, representing discrete amplitude values as binary codes. For example, a signal with an analog value of 5.00000542342:

- **5.00000542342 is the analog signal.**
- After quantization, the value is approximated to 5.
- Converting the discrete value to digital, **5 corresponds to binary 101.**

Reference: Understanding Analog-to-Digital Converters: Deciphering Resolution and Sampling Rate - Technical Articles (allaboutcircuits.com)